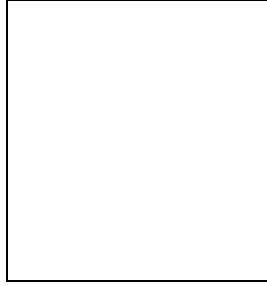


# A DEPARTURE FROM PREDICTION: ELECTROWEAK PHYSICS AT NUTEV

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The NuTeV collaboration has extracted the electroweak parameter,  $\sin^2 \theta_W$ , from the measurement of the ratios of neutral current to charged current neutrino and antineutrino deep inelastic scattering interactions. We find that our measurement, while in agreement with previous neutrino electroweak measurements, is not consistent with the prediction from global electroweak fits. To facilitate interpretation of the result, a model independent analysis is presented and possible explanations are discussed.

## Introduction

In deep inelastic neutrino-nucleon scattering, the weak mixing angle can be extracted from the ratio of neutral current (NC) to charged current (CC) total cross sections<sup>1</sup>:

$$\begin{aligned}
 R^\nu &\equiv \frac{\sigma(\nu_\mu N \rightarrow \nu_\mu X)}{\sigma(\nu_\mu N \rightarrow \mu^- X)} = \frac{\sigma_{NC}^\nu}{\sigma_{CC}^\nu} = g_L^2 + r g_R^2 \\
 &= \frac{1}{2} - \sin^2 \theta_W + \frac{5}{9} (1 + r) \sin^4 \theta_W \\
 R^{\bar{\nu}} &\equiv \frac{\sigma(\bar{\nu}_\mu N \rightarrow \bar{\nu}_\mu X)}{\sigma(\bar{\nu}_\mu N \rightarrow \mu^+ X)} = \frac{\sigma_{NC}^{\bar{\nu}}}{\sigma_{CC}^{\bar{\nu}}} = g_L^2 + \frac{1}{r} g_R^2 \\
 &= \frac{1}{2} - \sin^2 \theta_W + \frac{5}{9} \left(1 + \frac{1}{r}\right) \sin^4 \theta_W
 \end{aligned}$$

where  $r = \sigma_{CC}^{\bar{\nu}}/\sigma_{CC}^\nu$  and  $g_L^2 = 1/2 - \sin^2 \theta_W + 5/9 \sin^4 \theta_W$  and  $g_R^2 = 5/9 \sin^4 \theta_W$  are the left and right handed isoscalar quark couplings, respectively. The above relations are, of course, exact

only for tree level scattering off an isoscalar target composed of light quarks. Necessary adjustments to this idealized model include corrections for the non-isoscalar target, quark mixing, radiative effects, higher-twist processes, the longitudinal structure function ( $R_L$ ), the W and Z propagators, and the heavy quark content of the nucleon (charm and strange). Unfortunately, previous determinations of  $\sin^2 \theta_W$  measured using  $R^\nu$  suffered from large theoretical uncertainties associated with heavy quark production thresholds mainly affecting the CC denominator. These uncertainties, resulting from imprecise knowledge of the charm quark mass, dominated the CCFR measurement<sup>2</sup> and ultimately limited the precision of neutrino measurements of electroweak parameters. For example, combining the five most precise neutrino–nucleon measurements yielded a value of  $\sin^2 \theta_W^{\nu N} \equiv 1 - M_W^2/M_Z^2 = 0.2277 \pm 0.0036$ ,<sup>3</sup> thereby implying an equivalent W mass error of 190 MeV.

The Paschos–Wolfenstein combination<sup>4</sup> provides an alternative method for determining  $\sin^2 \theta_W$  that is much less dependent on the details of charm production and other sources of model uncertainty:

$$R^- = \frac{\sigma_{NC}^\nu - \sigma_{NC}^{\bar{\nu}}}{\sigma_{CC}^\nu - \sigma_{CC}^{\bar{\nu}}} = \frac{R^\nu - rR^{\bar{\nu}}}{1 - r} = \frac{1}{2} - \sin^2 \theta_W$$

Under the assumption that the neutrino–quark and antineutrino–antiquark cross sections are equal, use of the Paschos–Wolfenstein relation removes the effects of sea quark scattering which dominate the low  $x$  cross section. As a result,  $R^-$  is much less sensitive to heavy quark processes provided these contributions are the same for neutrinos and antineutrinos. The only remaining charm–producing contributors are  $d_v$  quarks which are not only Cabibbo suppressed but are also at higher fractional momentum,  $x$ , where the mass suppression is less of an effect.

Inspired by the Paschos–Wolfenstein technique, the measurement presented here extracts electroweak parameters from neutrino and antineutrino deep inelastic scattering reactions. However, NuTeV does not measure cross section ratios, such as those appearing in the above expressions ( $R^-$ ,  $R^\nu$ ,  $R^{\bar{\nu}}$ ) because of our inability to measure NC interactions down to zero recoil energy and because of the presence of experimental cuts, backgrounds, and detector acceptance. NuTeV instead measures experimental ratios of short to long events,  $R_{\text{exp}}^\nu$  and  $R_{\text{exp}}^{\bar{\nu}}$ . A detailed Monte Carlo simulation of the experiment then predicts these ratios and their dependence on electroweak parameters<sup>5</sup>. In the end, the NuTeV measurement has comparable precision to other experimental tests. Because neutrino scattering is a different physical process, NuTeV is sensitive to different new physics. In addition, NuTeV provides a precise measurement of NC neutrino couplings (the only other precise measurement is from the LEP I invisible line width), a measurement of processes at moderate space-like momentum transfers (as opposed to large time-like transfers probed at collider experiments), as well as a precise determination of the parameters of the model itself ( $\sin^2 \theta_W$ ,  $M_W$ ,  $\rho_0$ ,  $g_L^2$ , and  $g_R^2$ ).

## Results

From the high statistics samples of separately collected neutrino and antineutrino events and assuming the standard model, NuTeV finds:

$$\begin{aligned} \sin^2 \theta_W^{\nu N} \equiv 1 - M_W^2/M_Z^2 &= 0.2277 \pm 0.0013 \text{ (stat)} \pm 0.0009 \text{ (syst)} \\ &- 0.00022 \times \left( \frac{m_t^2 - (175 \text{ GeV})^2}{(50 \text{ GeV})^2} \right) \\ &+ 0.00032 \times \ln \left( \frac{m_H}{150 \text{ GeV}} \right) \end{aligned}$$

with the small residual dependence on  $m_t$  and  $m_H$  resulting from leading terms in the one-loop electroweak radiative corrections to the W and Z self energies<sup>8</sup>. The result lies three standard

deviations above the prediction from the global electroweak fit,  $0.2227 \pm 0.0004$ <sup>6,7</sup>. The measurement is currently the most precise determination of  $\sin^2 \theta_W$  in neutrino–nucleon scattering, surpassing its predecessors by a factor of two in precision, and is statistics–dominated. Within the standard model, the NuTeV measurement of  $\sin^2 \theta_W$  indirectly determines the W boson mass,  $M_W = 80.14 \pm 0.08$  GeV, with a precision comparable to individual direct measurements from high energy  $e^+e^-$  and  $p\bar{p}$  colliders; however, the nearly  $3.5\sigma$  deviation from the directly measured W mass,  $M_W = 80.45 \pm 0.04$  GeV, makes it especially difficult to explain the NuTeV result in terms of oblique radiative corrections<sup>9</sup>.

Relaxing the standard model assumptions, a model independent analysis recasts the same data into a measurement of effective left and right handed neutral current quark couplings. NuTeV measures:

$$\begin{aligned}(g_L^{\text{eff}})^2 &= 0.3001 \pm 0.0014 \\ (g_R^{\text{eff}})^2 &= 0.0308 \pm 0.0011\end{aligned}$$

with a correlation coefficient of  $-0.017$ . Comparing these couplings to their standard model values<sup>6</sup>,  $(g_L^{\text{eff}})_{\text{SM}}^2 = 0.3042$  and  $(g_R^{\text{eff}})_{\text{SM}}^2 = 0.0301$ , indicates that while the right handed coupling appears to be compatible with the prediction, the NuTeV data clearly prefer a smaller left handed effective coupling.

Lying  $3\sigma$  above the prediction of the standard electroweak theory, the NuTeV  $\sin^2 \theta_W$  result is surprising, however it is not immediately apparent what the cause of the discrepancy might be. In the following sections, we discuss the impact of the NuTeV result on global standard model fits, the plausibility of various explanations, and the prospects for future measurements of  $\sin^2 \theta_W$  at low energy.

## Impact on Standard Model Fit

Figure 1 exhibits the results of the LEP Electroweak Working Group (LEPEWWG) global fit<sup>6</sup> to all precision electroweak data including the NuTeV measurement of  $\sin^2 \theta_W$ . The largest pulls are coming from the NuTeV  $\sin^2 \theta_W$  result and the LEP II measurement of  $A_{FB}^{0,b}$ , both of which favor a large Higgs mass (Figure 2). The inclusion of NuTeV in the standard model fit increases the global  $\chi^2/\text{dof}$  to 28.8/15. The probability of the  $\chi^2$  being worse than 28.8 is only 1.7%. If one arbitrarily excludes the NuTeV results, the fit improves to a probability of 14.3% ( $\chi^2/\text{dof} = 19.6/14$ ), which itself is marginalized by the  $3\sigma$  discrepancy between the two most precise determinations of  $\sin^2 \theta_W$  at the Z pole: the leptonic measurement,  $A_{LR}$  at SLD, and the hadronic measurement,  $A_{FB}^{0,b}$  at LEP.

These results should, of course, be interpreted with caution. Discarding one or two measurements can improve the fit, but at the same time drastically change the predicted Higgs boson mass. If the two most discrepant measurements,  $A_{FB}^{0,b}$  and NuTeV  $\sin^2 \theta_W$ , are arbitrarily removed from the fit, the global  $\chi^2/\text{dof}$  improves to 6.84/9, a robust 65% probability<sup>10</sup>; however, the favored value of the Higgs mass drops to 43 GeV<sup>11</sup>, well below the direct search limits set by the non–discovery of the Higgs at LEP II,  $m_H > 114$  GeV.

Motivated by the large standard model fit  $\chi^2$ , we explore possible explanations for the NuTeV results in the following sections. In particular, we consider the effects of nuclear shadowing, isospin violating parton distribution functions, asymmetries in the nucleon strange sea, and additional  $Z'$  bosons.

## Nuclear Shadowing

If nuclear shadowing were significantly different for NC and CC neutrino interactions, such an effect would impact NuTeV’s measurement of  $\sin^2 \theta_W$ . In a recent comment<sup>12</sup>, Miller and

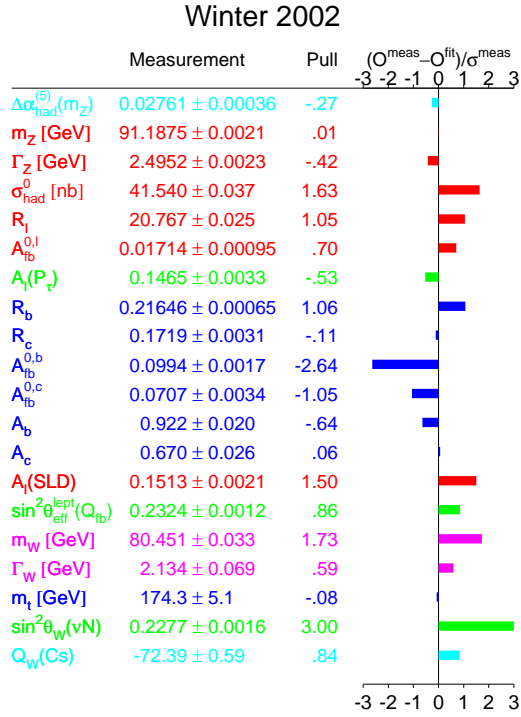


Figure 1: The current global electroweak fit including the NuTeV  $\sin^2\theta_W$  result. The horizontal bars indicate the pull of each measurement, in standard deviations, from its standard model expectation.

Plot is courtesy of the LEPWWG.

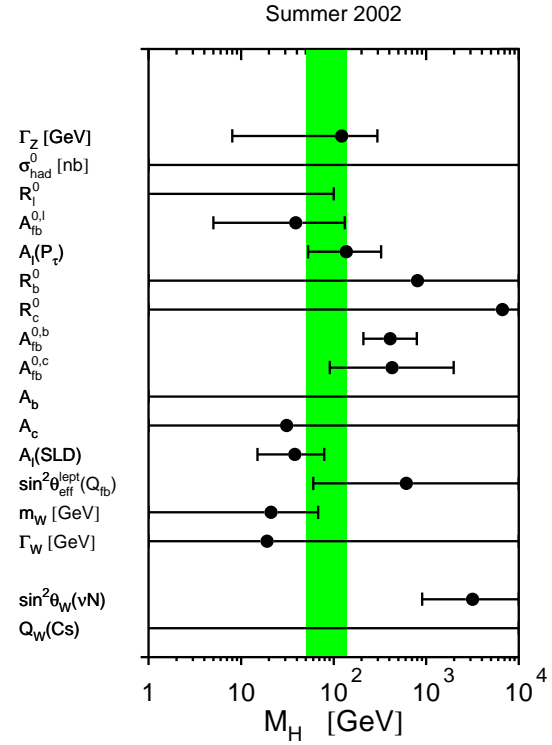


Figure 2: Sensitivity of the precision electroweak data to  $m_H$ . Most of the data is consistent with a low  $m_H$ , except for  $A_{FB}^{0,b}$  and NuTeV  $\sin^2\theta_W$ . Plot is courtesy of the LEPWWG.

Thomas consider a particular vector meson dominance (VMD) shadowing model that they claim is capable of accounting for the entire NuTeV discrepancy. However, as shadowing within the VMD model is weaker for  $Z^0$  exchange than for  $W^\pm$  exchange, the predictions for  $R^\nu$  and  $R^\bar{\nu}$  are thereby increased for a portion of the NuTeV data in the low  $Q^2$  shadowing region. The effect has the *wrong sign*, since NuTeV measures ratios for neutrino and antineutrino scattering processes,  $R_{\text{exp}}^\nu$  and  $R_{\text{exp}}^{\bar{\nu}}$ , which are both smaller than expected. More generally, because any model of differing neutral and charged current nuclear shadowing will change  $R_{\text{exp}}^\nu$  and  $R_{\text{exp}}^{\bar{\nu}}$  more than  $R^-$ , it is unlikely that any such model could explain the discrepancy in NuTeV's measurement of  $\sin^2\theta_W$ .

## Isospin Violations

The NuTeV result is extracted assuming isospin symmetry in the nucleon,  $u^p = d^n$ ,  $d^p = u^n$ ,  $\bar{u}^p = \bar{d}^n$ , and  $\bar{d}^p = \bar{u}^n$ . While all global parton distribution fits (CTEQ, GRV, MRST) are performed under this assumption, the NuTeV analysis is sensitive because of the need to assign  $u$  and  $d$  flavors (which possess different NC couplings) to the neutrino scatterers. Several classes of non-perturbative models have calculated the potential effect of isospin violation in the nucleon<sup>13,14,15</sup>. Estimating the effect of the single quark mass difference ( $m_d - m_u = 4.3$  MeV), the earliest calculation<sup>13</sup> predicts a large  $-0.0020$  shift in  $\sin^2\theta_W^{\text{NuTeV}}$ , which could account for roughly 40% of the observed discrepancy. However, more complete calculations that include differences in the nucleon masses ( $m_n - m_p = 1.3$  MeV), diquark masses ( $m_{dd} - m_{uu}$ ), and nucleon radii predict much smaller shifts in the result. For example, the Thomas *et al.* bag model calculation<sup>14</sup> predicts  $\delta\sin^2\theta_W^{\text{NuTeV}} = -0.0001$  as a result of the cancellation of opposing

shifts at low and high  $x$ . A meson cloud model prediction<sup>15</sup> yields a similarly small  $+0.0002$  shift in the NuTeV measurement. To shift the NuTeV  $\sin^2 \theta_W$  value down to its standard model expectation would require isospin violation at the level of  $\int x d_v^p(x) - x u_v^n(x) dx \sim 0.01$  (or 5% of  $\int x d_v^p(x) + x u_v^n(x) dx$ )<sup>16</sup>. While the more recent calculations do not suggest large isospin violation, such a possibility cannot be firmly excluded as a potential explanation for the NuTeV results. However, a nucleon isospin violating model which successfully accounts for the NuTeV discrepancy needs to be evaluated in the context of a global fit so as not to violate existing experimental data in the attempt to accommodate NuTeV.

### Strange Sea Asymmetry

The NuTeV analysis also assumes that the strange and anti-strange seas are symmetric,  $s(x) = \bar{s}(x)$ ; however it has been noted that non-perturbative QCD processes can potentially generate a momentum asymmetry between the strange and anti-strange seas<sup>20</sup>. Such an asymmetry can be directly measured using the same parton distribution formalism and cross section model as were employed in the  $\sin^2 \theta_W$  measurement. Recall that in neutrino scattering, dimuon events are a clean signature of charged current charm production ( $\nu_\mu s \rightarrow \mu^- c$  and  $\bar{\nu}_\mu \bar{s} \rightarrow \mu^+ \bar{c}$ ) and hence allow independent extractions of strange and anti-strange quark distributions. Leading order fits to the NuTeV neutrino and antineutrino dimuon data samples<sup>21</sup> yield a negative momentum asymmetry:

$$\int x s(x) - x \bar{s}(x) dx = -0.0027 \pm 0.0013 \quad (1)$$

and a corresponding *increase* in the NuTeV measurement of  $\sin^2 \theta_W$ :

$$\sin^2 \theta_W = 0.2297 \pm 0.0019 \quad (2)$$

when compared to the result extracted assuming  $s(x) = \bar{s}(x)$ ,  $\sin^2 \theta_W = 0.2277 \pm 0.0016$ . Including the measured strange sea asymmetry *increases* the NuTeV discrepancy with the standard model to  $3.7\sigma$  significance, and hence, this is not a likely explanation. To explain the NuTeV  $\sin^2 \theta_W$  result would require a strange sea asymmetry,  $\int x s(x) - x \bar{s}(x) dx \sim +0.007$ , that is roughly 30% of  $\int x s(x) + x \bar{s}(x) dx$  and is in the opposite direction<sup>16</sup>.

### Extra $Z'$ Bosons

In addition to evaluating the effects of unexpected parton asymmetries<sup>16</sup>, we also consider several non-standard physics cases. The existence of an additional  $Z$  boson would impact the NuTeV measurement by shifting the effective neutrino-quark couplings away from their standard model values. These shifts can arise from both pure  $Z'$  exchange as well as from  $Z$ - $Z'$  mixing. A popular class of  $Z'$  models involves the introduction of extra  $U(1)$  symmetries. The  $E_6$  model in particular has been considered as a candidate for grand unified theories. In this specific model, the coupling shifts are well determined<sup>17</sup>, however because the NuTeV result requires an enhancement in the effective left-handed quark couplings, it is difficult to explain the entire discrepancy with the inclusion of such a  $Z'$ . While this specific model can produce large right-handed coupling shifts, appreciable  $Z$ - $Z'$  mixing is required to induce sizable shifts in the left-handed couplings. The size of the mixing is severely limited, at the  $\sim 10^{-3}$  level, by measurements from LEP and SLD<sup>18</sup>, hence making it difficult to accommodate the NuTeV measurement. On the other hand, it is possible to explain the entire NuTeV discrepancy with the inclusion of an “almost” sequential<sup>a</sup>  $Z'$  with a mass in the  $1.2^{+0.3}_{-0.2}$  TeV range. The present limits from Run I CDF and DØ direct

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<sup>a</sup> A  $Z'$  with standard couplings but which interferes destructively with the standard model  $Z$ .

searches set  $M_{Z'_{\text{SM}}} \gtrsim 700$  GeV at 95% confidence level<sup>19</sup>. Both the Tevatron Run II and the LHC offer the hope of discovering a  $Z'$  boson should it exist. Several authors have also recently discussed the NuTeV results in the context of other  $U(1)$  extensions and have found TeV scale  $Z'$ 's with specific couplings capable of explaining the NuTeV discrepancy<sup>22,23</sup>.

### Anomalous Neutrino NC Interaction

Finally, while such a solution is not model-independent or unique, it is interesting to interpret the entire NuTeV discrepancy as a deviation in the overall NC coupling strength  $\rho_0$ . The result is a neutral current rate that is 1% lower than the standard model expectation at almost  $3\sigma$  significance:

$$\rho_0^2 = 0.9884 \pm 0.0026 \text{ (stat)} \pm 0.0032 \text{ (syst)} \quad (3)$$

Unlike in the NuTeV fit for  $\sin^2 \theta_W$ , both the neutrino and antineutrino data are sensitive to  $\rho_0$ , so there is less control over the charm production uncertainties, and the systematics are therefore much larger.

Figure 3 displays the NuTeV result in comparison to all existing neutrino measurements. The only other precise experimental constraint is the LEP I measurement of Z decays into invisible channels from which the number of light neutrino species can be deduced. The LEP I result,  $N_\nu = 3 \cdot \frac{\Gamma_{\text{meas}}(Z \rightarrow \nu\bar{\nu})}{\Gamma_{\text{SM}}(Z \rightarrow \nu\bar{\nu})} = 3 \cdot (0.9947 \pm 0.0028)$ , is two standard deviations shy of the three known neutrino species<sup>6</sup>. Given this particular interpretation, one might suspect the neutral current couplings of neutrinos since the only two precise measurements are both lower than the standard model expectation. In fact, models capable of accommodating both the LEP I neutrino deficit and the NuTeV result have been recently proposed in the literature<sup>24</sup>.

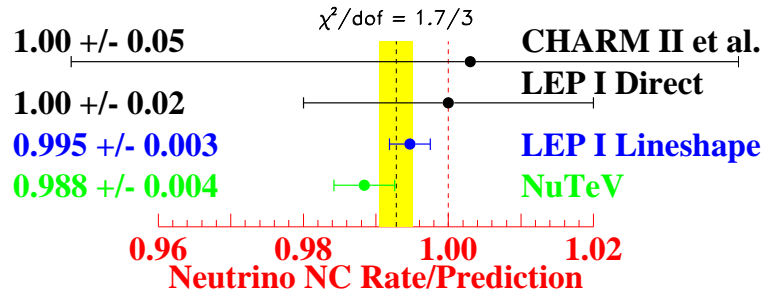


Figure 3: Experimental constraints on neutrino neutral current interaction rates relative to the standard model expectation. The two precise measurements, LEP I  $\Gamma(Z \rightarrow \nu\bar{\nu})$  and NuTeV  $\rho_0^2$ , are both below expectation.

### The Low Energy Future

NuTeV was dismantled several years after data-taking and holds no hope of remeasuring electroweak parameters in neutrino scattering. While atomic parity violation measurements<sup>25</sup> will hopefully continue to improve, in addition, two future experiments are preparing to also test the low energy prediction of  $\sin^2 \theta_W$ . An  $e^+e^-$  Møller scattering experiment, E158 at SLAC<sup>26</sup>, and a polarized electron-proton scattering experiment, QWEAK at Jefferson Lab<sup>27</sup>, both plan to probe this low  $Q^2$  regime in the near future. If they too observe a significant deviation from the predicted  $\sin^2 \theta_W$  scaling, this would provide striking evidence for new physics. However, if the deviation in the NuTeV measurement somehow resulted from new physics specific only to the neutrino or muon sector (i.e. that is not flavor universal), then the discrepancy would not manifest itself in these two future experiments.

## Conclusions

NuTeV has achieved the precision to be an important test of the electroweak standard model. By measuring ratios of neutral to charged current interactions, NuTeV has precisely determined  $\sin^2 \theta_W$  and has found a discrepancy of three standard deviations from the standard model expectation. Models for new physics that are capable of explaining the NuTeV results tend to be exotic, but hopefully either future low or high energy experiments will provide a clue to the source of the discrepancy.

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